ELSEVIER

CrossMark

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 75 (2015) 999 – 1004

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

# Integration of μ-SOFC generator and ZEBRA batteries for domestic application and comparison with other μ-CHP technologies

V. Antonucci[a], G. Brunaccini[a], A. De Pascale[b]*, M. Ferraro[a], F. Melino[b], V. Orlandini[b], F. Sergi[a]

[a]*CNR-ITAE, Salita S. Lucia sopra Contesse 5,Messina, 98126, Italy*
[a]*Università di Bologna-DIN viale del risorgimento 2, Bologna, 40136, Italy*

**Abstract**

This study investigates the possibility to integrate a Solide Oxide Fuel Cell (SOFC) prime mover and ZEBRA batteries, with the aim to fulfill a domestic user energy demand and to reduce the primary energy consumption, thereby, to enhance the total efficiency in a μ-CHP (Combined Heat and Power) application on a yearly basis. A realistic operational sequence of the SOFC-ZEBRA integration has been calculated using simple logic conditions. Both electric and thermal integration have been considered, in order to exploit the SOFC residual heat for the battery stand-by feeding. The key advantage of this system architecture is that the SOFC is operated without major load variations close to constant load, resulting in longer lifetime and thus reducing total costs of operation. Eventually, a comparison with alternative μ-CHP technologies has been carried out, highlighting the SOFC-ZEBRA potential.


Peer-review under responsibility of Applied Energy Innovation Institute

*Keywords:* SOFC; ZEBRA batteries; CHP

## 1. Introduction

Domestic applications of innovative small scale Combined Heat and Power (CHP) prime movers are currently under attention [1], in order to locally fulfil the internal energy demand, reducing access to the external net and limiting primary energy consumption. Among CHP technologies, high temperature fuel cells offer high electric performance, e.g. for Solid Oxide Fuel Cell (SOFC) expected electric efficiency is about 50-60% and they could provide significant amount of heat, in comparison with other fuel cells [2], leading to potential values of overall CHP efficiency as high as 80-85%. Nevertheless, transient capability

* Corresponding author. Tel.: +39 051 2093318; fax: +39 051 2093313.
*E-mail address:* andrea.depascale@unibo.it


Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.335

of SOFC is quite limited, requiring additional design efforts and subsystems [3] to cope with variable load demand. In particular, in the domestic application case, SOFC can be improved via energy storage devices, to cope with the instantaneous demand-production mismatch. Several storage technologies are available, with the electrochemical devices best suited for small capacity installations, due to the technology readiness, with limited size, cost and high flexibility compared to kinetic, hydraulic, compressed-air, or super-capacitor storage solutions [4]. Sodium/Nickel Chloride electrochemical storage, also known as ZEBRA batteries, operating at high temperature, are intrinsically maintenance free, show long life and high reliability and are fully recyclable [5]; thus, they could be an option for SOFC integration and have been taken into account here. Aim of the study is the performance investigation of an integrated SOFC-ZEBRA system network, in order to assess if the battery could improve the CHP operation of the SOFC in a domestic application long term scenario.

## 2. SOFC characteristics and experimental performance

In this study, a small scale SOFC system, manufactured by SOFCpower[TM], rated for 500 W of electric power output, has been taken into account as μ-CHP device. Nameplate data of the SOFC system are reported in Table 1 and the internal SOFC layout is provided in Fig. 1, where the internal temperature levels, registered during measurements performed on the SOFC at the CNR laboratories, are highlighted. The fuel cell polarization curve and power curve have been obtained in experimental tests and are shown in Fig. 2a, while the part-load performance of the system are reported in Fig. 2b, showing electric and thermal efficiency, acquired by cooling exhaust gas down to 300°C. In particular, the SOFC base load internal operating temperature is close to 750°C, the corresponding exhaust gas temperature is 570°C, but a long startup time is required in order to reach full load and temperature set point.

Table 1. SOFC nameplate data and start-up time

| *Parameter* | unit | value |
|---|---|---|
| Electric power output | W | 500 |
| Max power density | W/cm$^2$ | 0.375 |
| Nominal electric DC efficiency | - | 45% |
| Peak DC electric efficiency | - | 50 % |
| Operating temperature | °C | 750 |
| weight | kg | 17.5 |
| Cold start-up time | min | 250 |

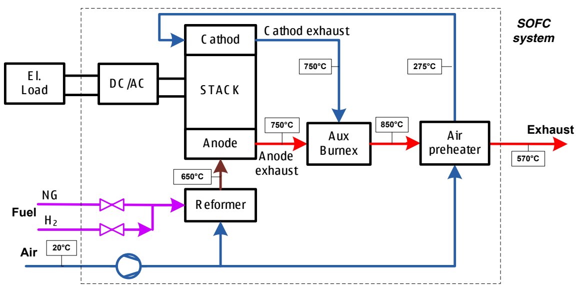



Fig. 1. SOFC internal layout

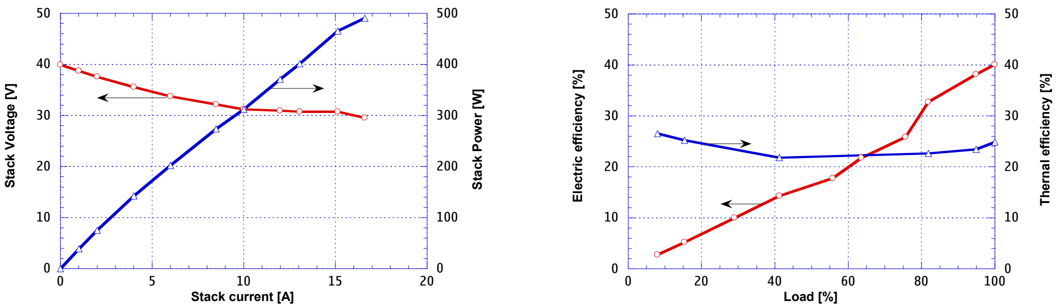



Fig. 2. SOFC experimental performance: (a) polarization and power curves; (b) part-load el./th. efficiency vs load

## 3. ZEBRA batteries characteristics

The above introduced SOFC system has been integrated with an electrochemical storage device. The considered battery is a ZEBRA type battery, which is based on the Sodium-Nickel Chloride technology (the positive electrode is made of $NiCl_2$, the negative electrode is liquid state Sodium, as far as the operating temperature is above 157°C [5]). Nevertheless, the optimal operating temperature of the ZEBRA battery ranges around 270-300°C, which is compatible with the SOFC outlet temperature. In particular the considered battery is a commercial Fiamm 48TL80 model, developed for stationary applications and rated for almost 4kWh of nominal capacity (i.e., 80 Ah, 48 V), with energy density equal to 81 Wh/kg and 80 Wh/liter. The optimal charging load curves are presented in Fig. 3, the power input should be limited (to 1.2 kW) and the ideal charging time should be 5 h. During stand-by periods of the battery, a constant energy absorption should be taken into account, to keep high the internal temperature.

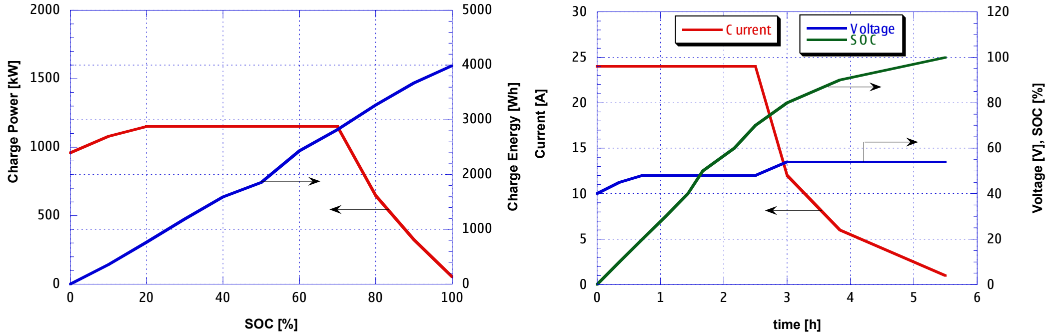



Fig. 3. (a) ZEBRA power vs SOC; (b) ZEBRA charging V-I characteristics

## 4. Integrated SOFC-ZEBRA system network for domestic application

A CHP system network based on the SOFC and ZEBRA is under investigation in this study for stationary domestic application. The considered network layout, with the included subcomponents and the related power flows, is shown in Fig. 4. The main included components are: (i) the SOFC μ-CHP system, (ii) the ZEBRA Electric Energy Storage (EES) system; (iii) the external electric net (NET); (iv) a Thermal Energy Storage (TES) system; (v) an auxiliary boiler (AUX); (vi) an energy user (USER).

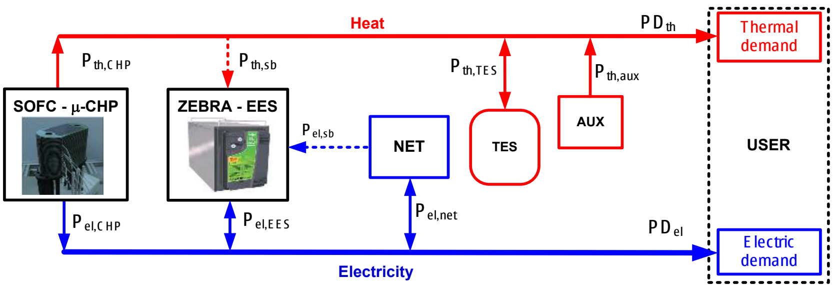



Fig. 4. Layout of the energy system network with components and power flows

### *4.1 Integrated SOFC-ZEBRA system network simulation*

A reasonable management logic of the system components has been taken into account and a calculation routine has been developed, to obtain the power flows at each time step. A "thermal load following" μ-CHP operation mode is assumed, i.e. the thermal power demand causes the thermal sources to be put into operation. In particular, the thermal power demand of the user ($PD_{th}$) is fulfilled by: the SOFC thermal output ($P_{th,CHP}$); by the TES output ($P_{th,TES}$); and by the AUX output ($P_{th,AUX}$), with this order of priority. If a surplus of the μ-CHP thermal production occurs in comparison with the instantaneous $P_{th,d}$, the surplus is stored in the TES and the AUX is switched-off. The electric power demand ($PD_{el}$) is fulfilled by: the SOFC electric output ($P_{el,CHP}$); by the EES output ($P_{el,EES}$); and by the NET contribution ($P_{el,NET}$), with the given order of priority. The electric power surplus is stored in the EES, or delivered to the NET, if the EES is in its maximum State of Charge (SOC) condition. If the electric demand is higher than the μ-CHP generation plus the EES power contribution, the NET provides the residual electricity. The SOC of the EES is updated at each time step.

Two network configurations have been taken into account and compared in this study, named as "electric stand-by" and "thermal stand-by" respectively. In the first case, the thermal power required by the ZEBRA battery to keep constant the internal temperature conditions during stand-by periods is provided by an electric resistance fed by the SOFC system through the NET (dotted blue line in Fig. 4). This case was preliminary investigated in [6] and it corresponds to the conventional ZEBRA battery configuration. In the second case, investigated in this study, the stand-by thermal power is directly provided by the SOFC (red dotted line in Fig. 4), eliminating the electric consumption for stand-by. The thermal power consumption due to stand-by ($P_{th,sb}$) has been considered in the calculations as an additional contribution to the thermal demand. The stand-by periods occurrence depends on the electric power flows, which are depending on the thermal flows, according to the used "thermal load following" management logic. Thus, an iterative calculation procedure has been implemented to obtain the final electric and thermal flows, including the stand-by power flows.

In order to realize the thermal stand-by configuration, the hot gas line downstream the SOFC has been adapted and optimized with the introduction of two heat exchangers, namely HX1and HX2 (Fig. 5): HX1 is located upstream the EES, to cool the exhaust gas to temperature level compatible with the ZEBRA optimal operation and HX2 is downstream the ZEBRA, to recover additional thermal power available for the domestic user. The operating ZEBRA temperature has been considered equal to 270°C, with the exhaust gas temperature after HX1 equal to 350°C and after HX2 equal to 120°C while the cooling water outlet/return temperature constraints have been set equal to 60°C/90°C respectively, compatible with a domestic user. The yearly electric and thermal load profiles of a typical single domestic user have been taken into account in this study (see Fig. 6), as elaborated in [6]. A domestic user with thermal peak equal to 12.6 kW and electric peak equal to 2.3 kW has been considered.

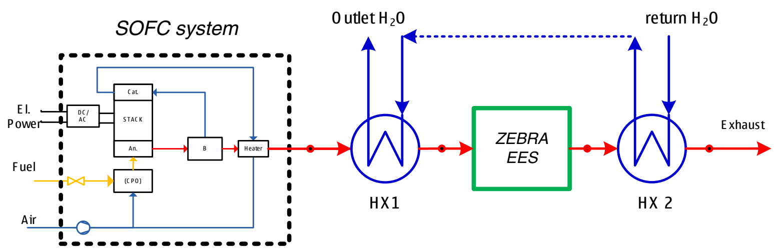



Fig. 5. The hot gas line for CHP operation with "thermal stand-by"

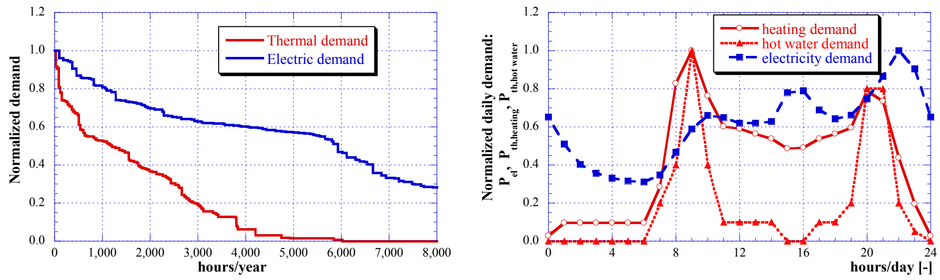



Fig. 6. Electric and thermal USER demand, normalized with peak value: yearly monotonic curves (a); typical daily profiles (b)

## 5. Summary of results and comparison with other prime movers

Given the above described demand and the SOFC operation management assumptions, the calculated number of SOFC operating equivalent hours is equal to the entire thermal year (i.e., 4392 h). A summary of the system electric and thermal energy balance calculated on yearly basis is provided in Table 2, for the two scenarios of "electric stand-by" and "thermal stand-by" of the ZEBRA. The comparison shows the possibility, with the 2$^{nd}$ scenario, to increase the amount of electricity sold to the NET, with a limited negative impact on the thermal energy provided by the AUX boiler.

A comparison has been performed between the SOFC system and various alternative µ-CHP systems in the range of power size up to 5 kW, namely four ICEs, two Stirling Engines (SE), two Micro Rankine Cycles (MRC), one Micro Gas Turbine (MGT) and one Thermo-PhotoVoltaic (TPV) prototype. Results of the µ-CHP systems integrated with ZEBRA, are shown in Fig. 7 and Fig. 8. In particular, the primary energy savings per installed electric power of the µ-CHP prime mover has been calculated in comparison with a reference non-CHP scenario (where the user energy demand is covered by the net and by a conventional boiler) and it is provided in Fig. 7-a and 7-b, for "electric stand-by" and "thermal stand-by" respectively. The SOFC-based µ-CHP system provides values of primary energy savings around 1000 kWh/year per installed kW, in line with the other technologies (but other few cases can reach larger values, i.e. 3000-4000 kWh/y/kW). The "thermal stand-by" case provides slightly better performance. Moreover, a comparative economic analysis has been performed considering the Italian electricity and natural gas tariff scenario. Fig. 8 shows results of the admissible investment cost of the µ-CHP system per unit of installed electric power, assuming a 10 year horizon; larger values of admissible investment cost occur in case of the SOFC system and results are not significantly affected by the ZEBRA stand-by case.

Table 2. SOFC –ZEBRA energy balance for a one thermal year of operation - domestic user

| **THERMAL ENERGY yearly balance** *[kWh]* | | |
|---|---|---|
| *Energy term* | *El. stand-by* | *Th. stand-by* |
| USER demand | 20000 | 20000 |
| SOFC output | 2393 | 2584 |
| Stored and delivered by TES | 700 | 667 |
| EES thermal absorption | 0 | 191 |
| From SOFC to USER | 1693 | 1534 |
| From AUX | 17607 | 17798 |

| **ELECTRIC ENERGY yearly balance** *[kWh]* | | |
|---|---|---|
| *Energy term* | *El. stand-by* | *Th. stand-by* |
| USER demand | 1458 | 1458 |
| SOFC output | 2152 | 2152 |
| Stored in EES | 556 | 556 |
| EES electric absorption | 191 | 0 |
| From SOFC to NET | 499 | 691 |
| Form NET | 0 | 0 |

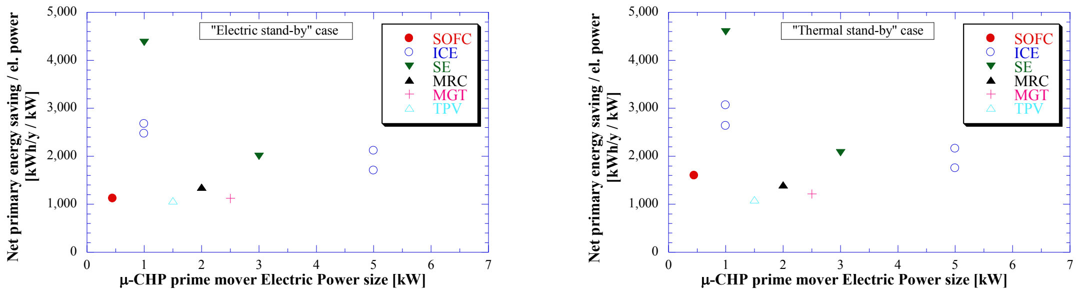



Fig. 7. Primary energy savings - Comparison of SOFC and other micro-CHP systems: a) electric-stand-by; b)thermal stand-by.

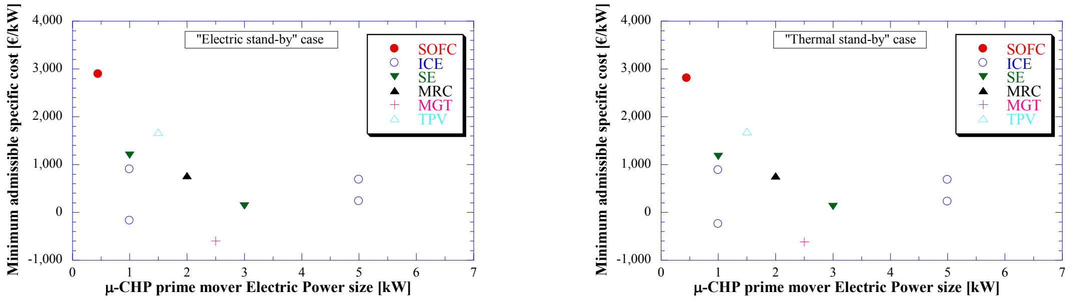



Fig. 8. Admissible investment cost- Comparison of SOFC and other micro-CHP systems: a) electric-stand-by; b)thermal stand-by.

## 6. Conclusions

The carried out preliminary study on a SOFC-ZEBRA integrated CHP system demonstrated the viability of the solution, in terms of overall energy and economic performance, for domestic application. The paper, based on experimental data acquired on a μ-SOFC stack and on ZEBRA data, showed the possibility to thermally integrate the two components, achieving improvement in primary energy savings.

## References

[1] V. Kuhn, J. Klemes, I. Bulatov. *Appl. Therm. Eng*. 2008; **28** (16): 2039-2048.

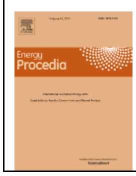
[2] B. Belvedere, M. Bianchi, A. Borghetti, A. De Pascale, M. Paolone, R. Vecci. Experimental analysis of a PEM fuel cell performance at variable load with anodic exhaust management optimization. *Int J Hydrogen Energy*, 2013; **38** (1): 385-393

[3] L. Barelli, G. Bidini, A. Ottaviano. *Applied Energy* 2013;**110**: 173–189

[4] X. Luo, J.Wang, M. Dooner, J. Clarke. *Applied energy*, 2014, in press

[5] Sudworth JL. The sodium/nickel chloride (ZEBRA) battery. *J Power Sources*, 2001;**100**:149–63.

[6] M. Bianchi , A. De Pascale, F. Melino, Performance Analysis of an Integrated CHP System with Thermal and Electric Energy Storage for Residential Application , *Applied Energy*, 2013;. **112**: 928-938




### Biography

Andrea De Pascale is assistant professor at University of Bologna. His scientific activities cover numerical and experimental aspects of advanced energy systems, such as fuel cells, organic Rankine cycles and CHP applications.